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Magnetic field in galaxies, galaxy clusters, and intergalactic space

Arnon Dar

Department of Physics and Space Research Institute, Technion, Haifa 32000, Israel and Theory Unit, CERN, 1211 Geneva 23, Switzerland

A. De Rújula

Theory Unit, CERN, 1211 Geneva 23, Switzerland and Physics Department, Boston University, Boston, Massachusetts, USA

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Magnetic fields of unknown origin appear to permeate the Universe on all large scales. We suggest that the winds and cosmic rays, which are produced by the spherical ejecta and jets from supernova explosions, magnetize the interstellar medium in galaxies, the intracluster medium in galaxy clusters, and the intergalactic space. We show that, if the cosmic rays generate magnetic fields in rough energy equipartition with the cosmic rays, the predicted magnetic-field strengths coincide with the ones observed.

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The average magnetic field (MF) of the interstellar medium (ISM) of our Galaxy ($B_{\rm MW} \sim 5\ \mu$G) corresponds to an energy density of $\sim$0.5 eV cm^{-3}, in good agreement with the energy density of galactic cosmic rays (CRs) [1]. This provides a strong hint of a common origin and of energy equipartition [2], though other theories of the origin of galactic fields—such as dynamo amplification of primordial seed fields—have been proposed [3].

The origin of intergalactic MFs, both within and without galaxy clusters, is also undecided. Radio observations of galaxy clusters indicate that the *intra*-cluster medium (ICM) between the galaxies is permeated by intense MFs [4]. Nearby clusters are seen to have a "radio halo" with a distribution similar to that of the cluster gas, observed in x rays. These halos are produced by synchrotron emission from CR electrons spiraling in the cluster's MF, while the x rays are electron bremsstrahlung. Measurements of the Faraday rotation of linearly polarized radio emission traversing the cluster's medium, in combination with x-ray data, support the existence of cluster MFs of a few μG [5,6]. The mapping of the Faraday rotation reveals that the clusters' MFs are turbulent with a Kolmogoroff power spectrum on a variety of scales [7].

The MF between clusters and isolated galaxies in the *inter*-galactic medium (IGM) is not known. Speculations on its value range from nearly a μG to a pG. Low-level radio emission was detected from the IGM around Coma [6] and from the IGM in large-scale filaments of galaxies [8]. The estimated field strengths are of the order of several hundred nG.

Theories of the origin of MFs in the ICM and IGM include cosmic shocks [9], ionization fronts [10] and outflows from primeval galaxies [4], quasars and/or radio galaxies [11]. In particular, Kronberg *et al.* have estimated [12] that "giant" extragalactic radio sources, powered by accretion onto massive black holes ($M > 10^8\ M_\odot$), inject $E_B \sim 10^{60-61}$ erg of magnetic energy into radio lobes, and have argued that the expansion and diffusion of these Mpc-scale lobes could have magnetized a large fraction of the IGM. Assuming that in the accretion $\sim$1% of M is released in the form of magnetic energy, they estimated a mean $B_{\rm IGM} \sim 40$ nG at redshift $z \sim 2$. This value later evolves as $(1+z)^2$ due to cosmic expansion, yielding a two-orders-of-magnitude smaller IGM energy density, and a one-order-of-magnitude smaller $B_{\rm IGM}$ at $z = 0$.

Concerning the ICM, it was suggested that the jets formed by accretion onto massive black holes in clusters provide the heat source in the so-called "cooling flow" (CF) clusters [13]. But it was also found [12] that the radio lobes of the powerful radio galaxies at the center of rich clusters contain a magnetic energy of only $E_B \sim 10^{58-59}$ erg. Assuming equipartition between the kinetic energy output and the magnetic energy, the energy supply from such objects is insufficient to power the x-ray emission from bright CF clusters over a Hubble time ($\sim 10^{62}$ erg for x-ray bright CF clusters). Moreover, some CF clusters contain neither powerful radio galaxies nor active galactic nuclei. Contrariwise, it was shown [14] that the required heat supply in CF clusters can be provided by the energy deposited in the ICM by jets and CRs emitted from the cluster galaxies, and that the equipartition of energy between the ionized gas, the MF, and the CRs can explain the origin of MFs of several μG. For the CRs to be the heating agent of the cluster gas, the CR luminosity of a galaxy must be [14] a few times its "classic" estimate [15]. For the related interpretation of the gamma-background radiation to succeed, the jets must travel a few kpc or more [16]. Both requirements are predictions of the "cannonball" model of high-energy astrophysics [17].

There is mounting evidence from gamma-ray bursts [17], from SN1987A [18] and from x-ray and infrared observations of the Cassiopeia A supernova (SN) remnant [19], that in addition to quasispherical ejecta, supernovas (SNe) produce highly relativistic and narrowly collimated jets of ordinary matter, which carry an average kinetic energy $E_K[\rm Jet] \sim 2 \times 10^{51}$ erg, similar to the observed kinetic energy of the spherical ejecta. The jets slow down by collisions with the interstellar matter (ISM) along their path. The intercepted ISM is thereby accelerated to CR energies, carrying away almost entirely the original energy of the jets. This simple theory of CRs agrees very well with the observed CR spectra and CR composition at all relativistic energies [20].

In this paper we suggest that the bulk of the MFs in the ISM in galaxies, in the ICM in galaxy clusters, and in the IGM outside galaxy clusters could have a common origin: the outflow of jets, CRs, and winds [21] from SN explosions in star formation regions, where most SNe take place. These outflows may magnetize the ISM in galaxies, the ICM in galaxy clusters, and the IGM outside galaxy clusters, and establish an equipartition between the magnetic-field energy density with the corresponding local energy densities of CRs. We assume equipartition in the sense that, of the total kinetic energy ($\sim 2E_K$[Jet]) of the spherical ejecta and jets, 1/2 ends up in CRs.

Our main assumption of a rough local equipartition between magnetic-field energy density and the energy density of CRs has been widely used in astrophysics. It is motivated by astrophysical observations [2] and by "first-principle" numerical simulations which show that a relativistic plasma (in our case, the CRs) impinging on a medium at rest generates turbulence and MFs efficiently and very rapidly [22], although equipartition has not yet been derived rigorously or demonstrated numerically. We show that the equipartition assumption predicts MFs in the ISM, ICM, and IGM with strengths consistent with those observed. In large structures, the predicted magnetic energy density is roughly proportional to the luminosity density, with a mean MF of several μG in the ICM of rich galaxy clusters and ~60 nG in the IGM.

Our theory of large-scale MFs is part of a unified theory of high-energy astrophysics which also offers simple and successful explanations of the origin and properties of diverse phenomena such as gamma-ray bursts, x-ray flashes (XRFs) and their afterglows [17], cosmic rays [20], the diffuse "gamma-background radiation" [16], and the x-ray emission from "cooling flow galaxy clusters" [14].

Galactic cosmic rays, magnetic fields, and supernova explosions.—As a result of the steep energy spectrum of galactic CRs, the bulk of the CR energy is carried by nuclei with an average energy of a few GeV. The most accurate measurements of their flux, dI/dE, near the Earth and during solar minimum (minimum solar modulation) are those of AMS [1] and BESS [23]. Their measurements yield a local CR energy density [24]

$$\rho_E[\mathrm{CR}] = \frac{4\pi}{c}\int \frac{dI}{dE} E dE \approx 0.5\ \mathrm{eV\ cm^{-3}}. \qquad (1)$$

If the energy densities of galactic CRs and MFs are in equipartition,

$$B^2_{\mathrm{MW}}/(8\pi) \approx \rho_E[\mathrm{CR}], \qquad (2)$$

and $B_{\mathrm{MW}} \sim 5\ \mu$G, in good agreement with observations, as is well known (Longair 1992).

Can the bulk of the galactic CRs be accelerated by the spherical ejecta and relativistic jets from SN explosions? If the kinetic energy released by SNe is converted to CRs and MFs in approximate energy equipartition, the galactic CR luminosity must satisfy

$$L_{\mathrm{CR}}[\mathrm{MW}] \approx \frac{4\pi V_{\mathrm{CR}}[\mathrm{MW}]}{c}\int \frac{dI}{dE}\frac{E}{\tau(E)} dE \approx R_{\mathrm{SN}}[\mathrm{MW}]E_K[\mathrm{Jet}] \approx 1.3 \times 10^{42}\ \mathrm{erg\ s^{-1}}, \qquad (3)$$

where V_{CR}[MW] is the confinement volume of low-energy CRs in the Galaxy, $\tau(E)$ is their mean confinement time, and R_{SN}[MW] is the present galactic SN rate. In the numerical result we have used the estimate $R_{\mathrm{SN}}[\mathrm{MW}] \approx 1/50\ \mathrm{y}^{-1}$, obtained from the rate and spatial distribution of historical SNe, the measured galactic extinction, and the quoted value of E_K[Jet]. This SN rate is also consistent with the value measured in the local universe: the SN rate is $2.8\ \mathrm{y}^{-1}$ [25] in a "fiducial sample" of 342 galaxies within the Virgo circle (whose total B-band luminosity is $1.35\,h^{-2} \times 10^{12}\,L^B_\odot$). For $h = 0.65$ (H_0 in units of 100 km $\mathrm{Mpc^{-1}\ s^{-1}}$) and the galactic luminosity $L_{\mathrm{MW}} \sim 2.4 \times 10^{10}\,L_\odot$, the result is the same: $R_{\mathrm{SN}}[\mathrm{MW}] \approx 1/50^{-1}$.

By fitting the diffuse gamma-ray emission of the Galaxy, as measured by EGRET [26], to the CR production rate of γ rays in a model of the galactic CR halo [15], a "leaky box" volume $V_{\mathrm{CR}}[\mathrm{MW}] \approx 6.6 \times 10^{68}\ \mathrm{cm}^3$—the volume of a cylinder with 30 kpc diameter and 8 kpc height—was obtained. Using the observed CR spectrum and $\tau(E) \sim 2 \times 10^7 (E/\mathrm{GeV})^{-0.5\pm0.15}$ y (inferred from the relative abundance of unstable isotopes in CRs), we obtain for the mean injection rate of CR energy per unit volume in the Milky Way $\dot{\rho}_E[\mathrm{CR}] \approx 6.2 \times 10^{-20}\ \mathrm{erg\ cm^{-3}\ y^{-1}}$, and consequently $L_{\mathrm{CR}}[\mathrm{MW}] \sim 1.2 \times 10^{42}\ \mathrm{erg\ s^{-1}}$. This number agrees [27] with the right-hand side of Eq. (4). From the above we conclude that SN explosions seem to be the source of the bulk of the CR and MF energies in the ISM of ordinary galaxies.

The magnetic field in the ICM of galaxy clusters.—Let $R(z)$ be the rate of SN events in a galaxy such as ours, at redshift z, or lookback time t. For a standard cosmology with $\Omega = \Omega_M + \Omega_\Lambda = 1$, $dt/dz = [\Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}/[H_0(1+z)]$, where $\Omega_M \approx 0.27$, $\Omega_\Lambda \approx 0.73$, and $H_0 \approx 65$ km $\mathrm{Mpc^{-1}\ s^{-1}}$. The SN rate is proportional to the star formation rate $R_{\mathrm{SF}}(z)$, so that $R(z) = R(0)R_{\mathrm{SF}}(z)/R_{\mathrm{SF}}(0)$. The observations [28] are $R(z) \sim R(0)(1+z)^\alpha$ with $\alpha \approx 3.6 \pm 0.4$ for $z \leq 1$ and $R(z) \approx R(1)([1+z]/2)^{0\pm0.5}$ for $1 \leq z \leq 5$, a redshift beyond which the relative volume is small. If the star formation history in a galaxy cluster (GC) is not very different from that in the Milky Way or the rest of the Universe, the cluster's SN rate is simply weighed by the ratio of luminosities: $R_{\mathrm{GC}}(z) \approx (L_{\mathrm{GC}}/L_{\mathrm{MW}})R(z)$. For reasonable MF coherence lengths, low-energy CRs do not diffuse out of a rich cluster during a Hubble time. Assuming that the cluster decouples from the Hubble expansion at a relatively early time, the total CR energy in their ICM is

$$E_{\rm CR}(z_o) = \frac{2}{3}\,\frac{E_K[{\rm Jet}]R_{\rm SN}[{\rm GC}]I[{\rm SF}]}{H_0}, \tag{4}$$

where

$$I[{\rm SF}] = \int_{z_o}^{\infty} \frac{R_{\rm SF}(z)}{R_{\rm SF}(0)}\,\frac{dz}{(1+z)\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}. \tag{5}$$

The factor 2 in Eq. (4) reflects the equality of energies of jetted and ''spherical'' ejecta; and the factor 1/3 reflects the energy equipartition between CRs, MFs, and the *dense* ICM plasma [29]. For $z_o = 0$, the integral in Eq. (4) is $\approx 3.7 \pm 1.7$, implying a CR energy density

$$\rho[{\rm ICM}] \sim \frac{L_{\rm GC}}{L_{\rm MW}}\,\frac{R_{\rm SN}[{\rm MW}]E_K[{\rm Jet}]}{H_0 V_{\rm GC}} \sim (0.31 \pm 0.16)\left(\frac{L_{\rm GC}}{10^{12}\,L_\odot}\right)\left(\frac{\rm Mpc}{R_{\rm GC}}\right)^3 \ {\rm eV\ cm^{-3}}. \tag{6}$$

If the CRs from SN explosions magnetize the ICM in the same way that they magnetize the ISM, the MF in the ICM has the same energy density as the CRs: $B^2_{\rm ICM}/(8\pi) \sim \rho_{\rm ECR}$. This prediction is in good agreement with observations. For instance, the observed luminosity of Coma within a radius of 1 Mpc is $L_{\rm Coma} \approx 3 \times 10^{12}\,L_\odot$ [30], implying a CR energy density, $\rho_E[{\rm CR}] \sim (0.93 \pm 0.48)$ eV cm^{-3}, and $B_{\rm Coma} \approx 6.1 \pm 1.4\ \mu$G, in agreement with the observed $\sim 6\ \mu$G [31].

Intergalactic cosmic rays and magnetic fields.—Let $R_{\rm SN}(z=0) \approx 10^{-4}$ Mpc^{-3} y^{-1} be the current local SN rate per comoving unit volume (the observed SN rate per unit luminosity within the Virgo circle, multiplied by $\rho_L \approx 1.2 \times 10^8\,L_\odot$ Mpc^{-3}, the mean luminosity density in the local universe). In a steady state, the injection rate of CRs into the IGM by a galaxy is equal to its CR production rate. Consequently, SN explosions in galaxies, at a cosmic time $t(z)$, inject energy into the IGM at a rate $\sim 2E_K[{\rm Jet}]R_{\rm SN}(z)$. Let $dN_{\rm SN}/dE$ be the CR spectrum produced by a single SN. Its energy dependence is that of $(dI/dE)/\tau(E)$, with dI/dE the observed CR spectrum, and $\tau(E)$ the CR residence time. In equipartition, its normalization is $\int(dN_{\rm SN}/dE)EdE = E_K[{\rm Jet}]$. The CR spectral density in the IGM at redshift z_o is

$$\begin{aligned} \frac{dn}{dE}(z_o) &= \frac{R_{\rm SN}(0)}{H_0}\int_{z_o}^{\infty} f(z,E)dz, \\ f(z,E) &= \frac{(1+z)^{-2}}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\,\frac{R_{\rm SF}(z)}{R_{\rm SF}(0)}\,\frac{dN_{\rm SN}}{dE'}, \\ E' &= (1+z)E. \end{aligned} \tag{7}$$

The present CR energy density of the IGM implied by equipartition and Eq. (7) is

$$\rho[{\rm IGM}] = \int \frac{dn}{dE}EdE \approx (1.1 \pm 0.6) \times 10^{-4}\ {\rm eV\ cm^{-3}}. \tag{8}$$

If the galactic winds and CRs from SN explosions magnetize the IGM in the same way that they magnetize the ISM, then, under the assumption of equipartition, the magnetic field in the IGM has the same energy density as the CRs: $B^2_{\rm IGM}/(8\pi) = \rho[{\rm IGM}]$. Hence the average strength of magnetic fields in the IGM is predicted to be $B_{\rm IGM} \sim 60 \pm 15$ nG. The estimated field in the outskirts of Coma (several hundred nG [5]) is intermediate between our expectations for the ICM and the IGM.

Conclusions.—There is compelling evidence that long-duration gamma-ray bursts are produced by relativistic jets ejected in core-collapse SN explosions, as long advocated in the cannonball model [17]. The jets, along their long paths (much larger than a galaxy's size), transfer essentially all of their energy to the local medium, which is accelerated to CR energies [17,20]. From ''first-principle'' simulations it is known that a relativistic plasma (in our case, the CRs) impinging on a medium at rest generates turbulence and MFs efficiently and very rapidly [22]. The generation of CRs and the subsequent MFs along the jet's path is fast: it occurs at nearly the speed of light. The continuous injection of highly relativistic jets, CRs, and winds from galaxies into the IGM generate sufficiently uniform MFs in equipartition with CRs in a time much shorter than Hubble's time—even SN winds at a modest few thousand km s^{-1} reaches, in a Hubble time, distances larger than the mean separation between galaxies.

In equilibrium, the CRs escaping a galaxy —or being generated by jets beyond the galaxy's confines—have the same spectrum, the CR ''source spectrum'': the observed spectrum deprived of the galactic confinement-time effect, as in Eq. (4). We have assumed equipartition between CR and MF energies in the low-density ISM and IGM, and between the energies of CRs, MFs, and the dense plasma of the hot central regions of the ICM. On this basis, we obtained $B_{\rm MW} \sim 5\ \mu$G for the mean magnetic field in the Galaxy, and $B_{\rm Coma} \sim 6\ \mu$G, the mean magnetic field in the ICM within 1 Mpc from the center of the Coma cluster (or similarly rich clusters), in agreement with the observations. The prediction for the IGM is $B_{\rm IGM} \sim 60$ nG. The observations in the outskirts of Coma are between our predictions for the ICM and the IGM, but not enough is known about the propagation of CRs in the IGM to claim that this is a success.

Although other accelerators—such as flaring stars, stellar winds, pulsars, microquasars, and massive black holes in active galactic nuclei—contribute to the production of nonsolar CRs, supernova explosions seem to be the dominant source of CRs [20], as speculated long ago [32]. Not only can the SN outflows accelerate the bulk of the high-energy CRs, but they can also magnetize the entire Universe at the observed level.

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